Open Heavy Flavor Results from STAR

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Heavy quarks: $m_{c/b} \gg \Lambda_{QCD}$, $T_{QGP(RHIC)}$
- Produced early in heavy-ion collisions through hard scatterings
- Experience the whole evolution of the system
  $\Rightarrow$ good probe of medium properties, e.g. transport parameters

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**Time Projection Chamber:**
Tracking, PID (dE/dx), |η|<1, 2π

**Time Of Flight detector:**
PID (1/β), |η|<0.9, 2π
Heavy Flavor Tracker

HFT:
- Silicon Strip Detector: $r \sim 22$ cm
- Intermediate Silicon Tracker: $r \sim 14$ cm
- PIXEL detector: $r \sim 2.8$ & 8 cm, MAPS, 20.7x20.7 µm$^2$, 0.4%$X_0(2016)$ thick, air-cooled
D⁰ pₜ Spectra

- Precise measurements of D⁰ spectra extended to low pₜ and non-central collisions with HFT from 2014 data
- Results consistent with the re-analyzed 2010/11 TPC analysis
$D^0 R_{AA}$

- $R_{AA} < 1$ in the 0-10% centrality interval for all $p_T$
- Suppression at high $p_T$ increases towards more central collisions
- Similar to $D$-mesons at LHC and high-$p_T$ pions at RHIC

STAR Preliminary

$\sqrt{s_{NN}} = 200$ GeV

(a) 0-10%

(b) 10-40%

(c) 40-80%

$Au+Au$, ±π, ±h

STAR, ALICE, LBT, Duke

ALICE: JHEP 03 (2016) 081
**D⁰ R_{CP} and \bar{D}⁰/D⁰ Ratio**

- Significant suppression at high p_T.
- Reasonable agreement with theoretical calculations.
- \bar{D}⁰/D⁰ ratio is larger than 1.

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**Graphical Analysis**

- **Au+Au @ 200 GeV**
  - STAR Preliminary
  - \(p_T\) distribution for different centrality bins:
    - **0-10%**
      - Significant suppression at high \(p_T\).
      - Reasonable agreement with theoretical calculations.
      - \(D^0/\bar{D}^0\) ratio is larger than 1.
    - **10-20%**
    - **20-40%**

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**Fit Results**

- **0-10%**
  - Fit: \(1.104 \pm 0.021\)
- **10-20%**
  - Fit: \(1.071 \pm 0.019, 1.060 \pm 0.015\)
- **40-60%**
  - Fit: \(1.073 \pm 0.022, 0.943 \pm 0.039\)
D⁰ Cross-section and Blast Wave Fit

- Total D⁰ cross-section is nearly independent of centrality, and smaller than in p+p. However, for p_T > 4 GeV/c it decreases with centrality.
- Blast Wave fits (p_T < 5 GeV/c) : suggests earlier freeze-out of D⁰
\( \Lambda_c \) and Heavy Quark Hadronization

- Strong enhancement of \( \Lambda_c/D^0 \) ratio seen in Au+Au collisions.
- Enhancement predicted from coalescence hadronization.
- Enhancements relative to PYTHIA also seen in p+p and p+Pb collisions at LHC.

\[ \frac{\Lambda_c/D^0}{(D^0+\bar{D}^0)} \]

\( \Lambda_c/D^0 \) in A+A

\( p_T \) and centrality dependence?

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**Λ_c Reconstruction**

- More than 50% improvement in signal significance with TMVA BDT
- Also new data from 2016
  → Effectively 4x more data

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**2014 (Rectangular) QM17**

- Au+Au @ 200GeV
- 10-60%

**2014+2016 (BDT)**

- Au+Au @ 200GeV
- 10-60%

**STAR Preliminary**

- $(\Lambda_c) = 108 \pm 21$
- $(\Lambda_c) = 233 \pm 22$

Significance = 10.8
**\( \Lambda_c/D^0 : p_T \) Dependence**

- Significant enhancement of \( \Lambda_c/D^0 \) compared to PYTHIA/fragmentation baseline
- The \( \Lambda_c/D^0 \) ratio is comparable with light flavor baryon-to-meson ratios
- Consistent with charm quark hadronization via coalescence
  -- higher than model predictions, particularly at higher \( p_T \)

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![Graph showing Baryon/Meson Ratios vs. Transverse Momentum](image-url)

- **STAR Preliminary**
- **Au+Au @ 200GeV**
- **Ko: three-quark (0-5%)**
- **Ko: di-quark (0-5%)**
- **Greco (0-20%)**
- **SHM**
- **PYTHIA**
Λ_c/D^0 : Centrality Dependence

- Λ_c/D^0 ratio increases from peripheral to central collisions, indicative of hot medium effects
- Ratio for peripheral Au+Au comparable with p+p value at 7 TeV

ALICE: arXiv:1712.09581
**D_s/D_0 Enhancement**

- Strong D_s/D_0 enhancement observed in central A+A collisions w.r.t fragmentation baseline
  - Strangeness enhancement and coalescence hadronization
- Enhancement is larger than model predictions, particularly at higher p_T

[Graph showing D_s/D_0 ratio vs. p_T for Au+Au collisions at 200 GeV]

*STAR Preliminary*

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Total Charm Cross-section

- Total charm cross-section is estimated from the various charm hadron measurements

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\[ D^0 \text{ yields are measured down to zero } p_T \]

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\[ \text{For } D^{+/0} \text{ and } D_s, \text{ levy fits to measured spectra are used for extrapolation.} \]

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\[ \text{For } \Lambda_c, \text{ three model fits to data are used and differences are included in systematics} \]

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<table>
<thead>
<tr>
<th>Charm Hadron</th>
<th>Cross Section $d\sigma/dy$ ((\mu b))</th>
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<tbody>
<tr>
<td>$D^0$</td>
<td>41 $\pm$ 1 $\pm$ 5</td>
</tr>
<tr>
<td>$D^+$</td>
<td>18 $\pm$ 1 $\pm$ 3</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>15 $\pm$ 1 $\pm$ 5</td>
</tr>
<tr>
<td>$\Lambda_c^+$</td>
<td>78 $\pm$ 13 $\pm$ 28*</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>152 $\pm$ 13 $\pm$ 29</td>
</tr>
<tr>
<td>AuAu 200 GeV (10-40%)</td>
<td></td>
</tr>
<tr>
<td>pp 200 GeV</td>
<td><strong>Total</strong></td>
</tr>
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* derived using $\Lambda_c^+/D^0$ ratio in 10-80%

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- Total charm cross-section is consistent with p+p value within uncertainties, but redistributed
D*+/D⁰ Ratio in Au+Au Collisions

- Possible hot medium effects:
  - D*+ life time could become shorter in hot medium
  - Re-scattering can lead to a yield loss

- D*+/D⁰ ratio in Au+Au collisions at 200 GeV is consistent with PYTHIA and with ALICE data at higher pₜ.

- Ratio of the integrated yields shows no strong centrality dependence

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2018 RHIC & AGS Annual Users' Meeting (BNL)
Non-prompt $D^0$

- Strong interaction of charm with the medium. How about bottom?
- $R_{AA}$ of non-prompt $D^0$ extracted from the measured non-prompt fraction
- Improved signal significance for non-prompt $D^0$ fraction using BDT. New result down to low $p_T$ with 2014+2016 data on the way

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2018 RHIC & AGS Annual Users' Meeting (BNL)
B Study from Non-prompt J/ψ & D⁰ & e

- Strong suppression for $B \to J/\psi$ and $D^0$ at high $p_T$.
- Indication of less suppression for $B \to e$ than $D \to e$ ($\sim 2\sigma$): consistent with $\Delta E_c > \Delta E_b$.
- Measurements with improved precision are on the way.

Note: $R_{AA}$ references (data vs. theory) are different for these comparisons. The decay kinematics needs to be unfolded for different channels.
D$^0$ Directed Flow ($v_1$)

- Charm and anti-charm quarks can be deflected differently by the initial EM field → difference between D$^0$ and $\overline{D}^0$ $v_1$ sensitive to EM field
- Charm quarks interact with bulk medium → D$^0$ $v_1$ sensitive to the initial tilt of the source (bulk)
- First observation of non-zero (negative) D$^0(\overline{D}^0)$ $v_1$ slope
- D$^0(\overline{D}^0)$ $v_1$-slope much larger than that of kaons
D⁰ Elliptic Flow (v₂)

- Published D⁰ v₂ from data taken during 2014
- Clear mass ordering for pₜ < 2 GeV/c
- Follows NCQ-scaling in mid-central (10 - 40%) collisions

*Phys Rev. Lett. 118, 212301 (2017)*
D\textsuperscript{0} Elliptic Flow (v\textsubscript{2})

- D\textsuperscript{0} v\textsubscript{2} measurement extended to 0-10% centrality with combined data from 2014 and 2016 runs
- NCQ-scaling test with improved precision
- Charm quarks gain significant flow! 2014+2016
Summary

• Strong modification of charm hadron spectra and hadrochemistry in A+A collisions. \( (D^0 R_{AA} \& R_{cp}, D_s/D^0, \Lambda_c/D^0, D^0 v_2, D^0 v_1) \).
  -- total charm quark cross-section conserved
  -- substantial energy loss & coalescence hadronization
  -- gain significant flow & may have achieved thermal equilibrium in the medium \( (D^0 v_2) \)
  -- first observation of non-zero directed flow \( (v_1) \) for \( D^0 \).

• Strong energy loss at high \( p_T \) for \( B \rightarrow J/\psi \), and \( B \rightarrow D^0 \) measurements. Indication of less energy loss for bottom \( (B \rightarrow e) \), and measurement with better precision on the way.
Summary II – Charm / Bottom

\[ \frac{R_{AA}(D^0)}{R_{AA}(\pi)} \sim v_2(D^0) \sim v_2(h) \text{ vs. } m_T \]

- lose significant energy
- gain significant flow

Experimental: precision measurement of bottom
Theoretical: converge on value of transport parameters

Next
Back up
**D^0 in AuAu (2010/2011 TPC Analysis) - I**

**Erratum: PRL 113 (2014) 142301**

1. Two mistakes were discovered in calculating TOF related efficiency corrections
   - Hybrid PID: algorithm inconsistently implemented in data analysis vs. efficiency calculation
   - a DCA_{xy} cut efficiency was included in the correction two times

2. p+p measurement: no issue discovered, but the p+p D^0 baseline used for R_{AA} is updated with latest knowledge of charm frag. ratios
   - considering the p_T dependence of D*/D^0 frag. ratio
   - latest world average of c->D^0 and c->D* frag. ratios

(D^0 at p_T<2 GeV/c + D* at 2-6 GeV/c, *PRD 86 (2012) 072012*)
**STAR preliminary**

\[ \text{Au+Au } \sqrt{s_{NN}} = 200 \text{ GeV} \]

Centrality 0-10%

- **Similar suppression for** \( D^0 \) **and** \( D^{+/−} \)
- **Spectra measurement was important for the total charm cross-section**
D*+ Production in Au+Au Collisions

- D*+ feeds down to D° yields $D^{*+} \rightarrow D^0 + \pi^+$
- Hot medium effects:
  - D*+ life time could become shorter in hot medium
  - Re-scattering can lead to loss of yield

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B Study from Non-prompt J/ψ & D⁰ & e

\[
R_{AA}^{B\rightarrow J/\psi} = \frac{f_{Au+Au}^{B\rightarrow J/\psi}(data)}{f_{p+p}^{B\rightarrow J/\psi}(theory)} R_{AA}^{inc. J/\psi}(data)
\]

\[
R_{AA}^{B\rightarrow e} = \frac{f_{Au+Au}^{B\rightarrow e}(data)}{f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc. e}(data)
\]

\[
R_{AA}^{B\rightarrow D^0} = \frac{1}{<N_{coll}>} \frac{f_{Au+Au}^{B\rightarrow D^0} \times dN_{incl. D^0/pt}/dp_T}{dN_{FONLL/pt}/dp_T}
\]

\[
R_{AA}^{D\rightarrow e} = \frac{1-f_{Au+Au}^{B\rightarrow e}(data)}{1-f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc. e}(data)
\]

Note: \( R_{AA} \) references (data vs. theory) are different for different channels

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2018 RHIC & AGS Annual Users' Meeting (BNL)
• The moving spectators can produce enormously large electromagnetic field ($eB \sim 10^{18} \text{ G at RHIC}$)

• Due to early production of heavy quarks ($\tau_{CQ} \sim 0.1 \text{ fm/c}$) positive and negative charm quarks (CQs) can get deflected by the initial EM force

• $D^0$ and $\bar{D}^0$ $v_1$ can offer insight into the early time EM fields
Directed flow ($v_1$) due to hydro

- Heavy quarks are produced according to Ncoll density: symmetric in rapidity
- At non-zero rapidity, CQs production points are shifted from the bulk
- This can induce larger $v_1$ in CQs than light flavors
- Magnitude of CQ $v_1$ depends on the drag parameter used in this model

$\rightarrow (v_1\text{-slope})_{CQ} \gg (v_1\text{-slope})_{LQ}$ CQs much more sensitive to the initial tilt than the charged hadrons